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THE THEORY OF COPPER DEPOSITION.

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During the past few years there has been a lively interest in the theory of the origin of ore deposits, and recently two works have been published by the Institute of Mining Engineers and by the *Engineering and Mining Journal,* which give a very good account of the present state of the controversy, and references enough to carry one pretty well over the whole field of the latter.† In these discussions our deposits of iron ore and copper of lake Superior have been frequently used as illustrations of the various theories by those who take part in the discussion. In view of these facts, it seems proper to give a review of what is known concerning the copper of lake Superior and of the theories regarding the same. There is also a practical interest involved in the discussion. As we shall shortly see, all the best authorities at present agree that the copper has been deposited by water, but there is some difference of opinion as to whether the water current is a descending one and copper was deposited and a circulation produced by gravity, or ascending, and the circulation due to one or more principal causes, which we may call as a common name, volcanic, meaning thereby that they are connected with the interior heat of the earth. Now, it is a common notion among the practical Cornish miners of the copper country, although I do not remember to have seen the statement in print, that the copper is liable to occur under high ground.

To understand what is meant by the expression "high ground," we must remember that at the present day the bulk of the copper is deposited in bedded lodes. It would be perhaps more correct to say that it comes from lodes whose strike

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* Advance sheets from the Annual Report for 1903, reprinted from *The Michigan Miner*, January and February, 1904. It should be understood that the title in a general magazine like the AMERICAN GEOLOGIST is too broad, for the article has reference solely to the deposits of Keweenaw Point, and the author does not wish to apply either facts or conclusions to other deposits, such as the sulphides, whose history he believes to be different.

† Genesis of ore deposits, Reprinted papers from Volumes xxiii, xxiv, xxx and xxxi of the Transactions of the American Institute of Mining Engineers. Published by the Institute at the office of the Secretary, New York City, 1902.

Ore Deposits, a discussion republished from the *Engineering and Mining Journal*, New York City, 1903.

See also *Geological Survey of Michigan*, vol. i, Part II, p. 43. Vol. vi, Part I, p. 216.

Yet more recent: Trans. Am. Inst Min. Eng., Oct., 1902. "Igneous Rocks and Circulating Waters as Factors in Ore Deposition." by J. F. KEMP; "Ore Deposits Near Igneous Contacts," by W. H. WEED, and discussion of same. Annual report of the State Geologist (of New Jersey), 1902. "Copper Deposits of New Jersey," by WALTER HARVEY WEED. "The Chemistry of Ore Deposition," by WALTER P. JENNEY.

is the same as that of the beds of the Keweenaw formation. It is commonly accumulated in the originally more porous parts of the beds. Sometimes these porous parts are sandstones and conglomerates, but more often they are porous upper parts of lava flows. It is, I believe, true that in many cases there are faults parallel to the bedding planes, or so nearly so that the difference has not been detected, which have had an important influence on the production of copper. In some cases we know there are such faults, which generally have a somewhat steeper dip than that of dips generally.*

Nevertheless, in a practical way the most characteristic feature of these lodes is the porous beds. Any one of these porous beds may contain copper and there are few of them, which are decomposed, that do not show some trace of copper. But the parts which are relatively rich, rich enough to be the sole object of interest to the miner, are rare, and the meaning of the idea that copper occurs along high ground is, as I understand it, that in following the outcrop of such lode, chutes of copper are liable to occur where the outcrop of the lode is extra high. Now there is some ground for this idea. If we take the Baltic lode, just developed, we find that in the Baltic, Trimountain and Champion mines this is rich, while just northeast, on section 16† the Atlantic mine has done a good deal of exploring without being able to find the lode. Rising once more on the high land we find the Isle Royale mine close to the deep trough of Portage lake, where, on the other side, is the Quincy mine, on high land again. The Sheldon and Columbia and Hancock mines, more down in the Portage Lake valley, do not appear to have been so successful. Going farther north, we find the Calumet & Hecla, Tamarack, Kearsarge and Wolverine mines, not very far from the Allouez gap on the southwestern side; on the northeastern side is the Mohawk mine. Nearer the gap is the Ahmeek property, which

* The top of the Calumet and Hecla is markedly slickensided. See also Volume vi Part II, pp. 86-94; the slide fault in the Central mine appears to be nearly parallel to the Kearsarge conglomerate. The accumulation of copper was in the vein above this slide, and on reaching the conglomerate they worked on top of it finding good copper ground.

The annual report of the Phoenix mine for 1901 shows in the section by DUNBAR D. SCOTT, the steeper fault slide in that mine, in the St Clair vein. The old Minnesota, now Michigan mine, had its largest deposit of copper where a steeper fissure intersected a lode. See the report of the Commissioner of Mineral Statistics for 1880, p. 76. Copper Handbook, 1902, p. 195.

† Volume vi, Part II, Plate 10.

is just being opened up and whose true value has not been determined. If the "high ground" notion has any substantial basis, its prospects would not be so good as those of the Mohawk and Wolverine mines, although it lies on the same lode and between them. The Phoenix mine and the Cliff lie on higher land, not far from the gap of Eagle river, and turning to the other end of the range we find the Minnesota and the National on one side and the Victoria on the other of the gap made by the Ontonagon river, while the Mass and Adventure lie on the high land between the Flint and the Fire Steel rivers.

Now, this grouping of mines in accordance with this notion that the copper occurs on the high ground may be due to the fact that the porous beds are usually eroded, and therefore not exposed, and not easily exploited or developed, except on high ground. It might also be suggested that the alterations which produce the copper had cemented these beds more firmly and had thus given a greater resistance to erosion, either by ice or by water. The copper itself, however, even in the richest mines, is only a small fraction of the rock, and is easily decomposed chemically, and so are some of the associated minerals, and, although at times, copper bearing amygdaloids, as the igneous porous beds are called, are more or less saturated with silica and epidote, I do not think those minerals are so characteristic of the copper-bearing lodes as to lead to a relatively greater elevation of such parts of the lode. However, there is room here for inquiry.

I leave to the last another possible explanation which has a more direct connection with the theory of the deposits of the copper. If the copper is deposited by descending waters, as Pumpelly, who has done by far the most work upon the subject, suggested, and the motion of these descending waters is determined by gravity, descending along the lodes at one branch of the inverted siphon and rising either in the same lode at a lower point of its outcrop, or in some cross fissure, which might very well be the cause of the gap in the range, then we can readily see that the greatest activity and circulation and greatest deposition of the copper consequently, should be beneath salient points of the outcrop of the lode. Take for instance, the Calumet & Hecla. That deposit outcrops 600 or

700 feet above Lake Superior, and the chute of the richer streaks in the deposit is northward, and we may imagine the waters working down in that direction to re-appear over in the Allouez gap or up some fissure which may possibly have determined the gap. We see, therefore, that the question as to whether the copper was deposited by waters circulating in one fashion or another has a practical interest in guiding the search for the richest parts of the lode. Moreover, Van Hise has suggested that the richer parts of the lode—called chutes—will be found beneath upward bends if the waters of deposition are ascending, beneath downward bends if the waters of deposition are descending. If he is right, which I doubt, in saying that the copper of the Michigan lodes are deposited by ascending waters, the southern end of the Ahmeek and the northern part of the Kearsarge properties should be extra productive according to Hubbard's map of the Allouez gap area (Volume VI., Part II., Plate VII.), but if the waters are descending, the same area should be lean.

In the first place we may premise that it is a settled question that the copper was deposited by water. All kinds of authority agree in this, although at one time a few geologists thought of its being inserted in a molten state. But native copper and native silver occur together, as they could not if they were melted. They would at once be alloyed. Jewelry is often made of sections of nuggets of copper and silver, popularly known as halfbreeds, where the sharp and irregular line between the copper and silver is beautifully displayed. We also find copper grown upon minerals, like analcite and prehnite, which one can fuse in a candle flame. It is not very rare to find a sharp crystal of dog-tooth spar entirely plated over with copper, and then the growth taken up again.* Pumpelly has given in Volume I. of our reports a most thorough discussion of the way in which the copper occurs. A very interesting specimen, owned by Dr. Hubbard, shows a crystal of quartz which has been corroded and mainly by native copper. Moreover, in the deeper part of the Quincey mines, Dr. Koenig has found a water which is now depositing copper and contains 9 grams to the metric ton of the same.

* See Volume i, Part II, Chapter III; also Volume vi, Part II, pp. 163 to 165 of our reports.

I have shown in my United States Geological Survey water supply paper No. 31, on the different waters of Lower Michigan, that while each porous bed varies in its character of water from point to point, yet there is little intercommunication between them and it is difficult to see how there could be much, except upward along fissures or drill holes. Beds of clay or shale are known to be so impervious to water and to oil, they may be taken to be, even in a geological sense, impervious layers, permanently guiding and separating the different flows of water. The same statement applies to clayey belts of decomposed rock, paint rock and fluccan, as Van Hise himself has ably pointed out in discussing chutes and the formation of the Galena lead deposits. Thus, it must be remembered, that Van Hise's figures of underground flow apply only to a homogeneous medium. His figure 5, for instance, might represent the flow of water in one single porous bed, say of conglomerate, sandstone, or amygdaloid, but not the formation at random. It is by no means practically true, therefore, that the zone of fracture "will be searched to its base by moving waters," unless first it is not only potentially but really fractured, so as to make it practically porous as a whole, and unless, also, it is covered by a surface topography so rough as to stimulate circulation. These two conditions will be best fulfilled in those mountainous districts, which as Van Hise remarks, are most liable to contain ore deposits, page 416.

Now, the difficulty in supposing that the copper deposits are due to such a general circulation of water taken in at the surface, as Van Hise imagines are very great. The following is a sample of water from the Arcadian shaft, a relatively shallow shaft, analyzed by Dr. Koenig, August 23, 1898:

$CaCO_3$	32.7
Fe_2O_3	13.7
Kaolin	100.0
$FeCO_3$	24.5
$MgCO_3$	25.6
K_2CO_3	10.9
Na_2SiO_3	101.3
$NaCl$	tr.
$Na_3P_2O_5$	2.2
Na_2CO_3	42.3
Organic matter	82.0
Total	435.2

While a deep mine water coming in at the 46th level of the Quincy, analyzed by Dr. Koenig, was as follows:

Sp. Gr.	1.1898
$Ca\ Cl_2$	17.91
$Na\ Cl$	2.96
$Mg\ Cl_2$	———
SO_3	0
Iron	0.004
Copper	0.009
CO_2	0.00

Now these two analyses are typical.

The deep waters are strong solutions of earthy chlorides. A water with nearly 1 per cent. of bromine oozes in the 45th level of the Tamarack. The shallow waters are high in alkalies, and so low in chlorine that the alkalies have to be combined with other acids. It is no wonder that alkaline zeolites occur in the upper levels. One might explain the loss of carbonates if the upper water was descending by a precipitation of the same such as we know has taken place, but I do not see that we can so explain the presence and absence of chlorine. That must, it seems to me, have been an original constituent of the deeper rock moisture, either of the sea in which the rocks were laid down, or of the igneous magna. Prof. Moore in his presidential address before the Liverpool Geological Society (1903, p. 269) has shown that at the top of a 96 foot thick intrusive sheet there is a 10 to 15 foot belt, corresponding to the amygdaloids of the Keweenawan series, which contains a little over 4 per cent. carbonic oxide and 2.6 per cent. water which are, as he believes, probably primary. Analysis of the Lighthouse Point dyke, which is probably one of the Keweenaw flow feeders, shows chlorine, more than enough to go with $P_2 O_5$ for apatite, and the apatite which has been so commonly observed (Vol. VI, Part 1) also contains chlorine.

Note the apparent concentration of the early formed olivine at the margin.

Moreover around volcanic centers the escape of vapors containing chlorine and carbonic oxide and the formation of crusts of iron chloride are common.

Pumpelly furthermore concludes that the water which deposited the copper was descending. One of the arguments which he used is that the alkaline silicates abound in the upper

ANALYSES OF STONE FROM LIGHTHOUSE POINT MARQUETTE.

			June 30, 1903.	
SiO_2	46 98	47.67	57.25	47.10
Al_2O_3	17.85	17.55	18.10	17.47
Fe_2O_3	3.13	2.51	2.21	2.66
FeO	10.30	12.69	12.42	12.93
MgO	7.10	5.65	6.35	6.88
CaO	8 47	10.75	11.45	10.27
Sodium Oxide	2.04	2.21	1.98	1.91
Potassium Oxide	.60	.65	.66	.59
H_2O at about 800° C	1 97	.35		
H_2O at 110° C	1.55	·40		
CO_2	.20	.18		
P_2O_5	.143	.169	.158	.161
S	.097	.183	.086	.111
Cl	.07	.05	.02	.09
MnO	.26	.19	.18	.15
	101.880	102.422	100.744	109.522
Distance from margin	Margin	616m	4115m	Center 7600m

E. E. WARE under direction of E. D. CAMPBELL.

levels and are (page 40) rare in depth; "in other words they are abundant in that zone of the veins which lies between walls of those portions of the beds of the melaphyre in which we should look for the most advanced stages of alteration in the components of melaphyre supposing such alteration to be due to the action of descending solution." By alkaline silicates he means analcite, apophyllite, orthoclase (and datolite is of the same age). Copper occurs of similar age in some of these deposits. In studying the alteration of the lava flows which form so large a proportion of the Keweenawan series, I find that the olivine is first to alter, then the augite, and lastly the feldspar.

There are other arguments which may be used to support Pumpelly's theory with regard to the origin of copper. As has been said, down to say 500 or 600 feet the water of the mine is quite fresh. In the deeper mines while there is very little water it is an extremely strong solution of chlorides. The line between the two classes of water is reported to be very sharp, and there is a chance for a very interesting investigation right here. It would seem quite difficult to suppose a circulation of this heavy water up into a light fresh water, especially under high ground, and to imagine that there could be a sharp line between them. One would expect to find brackish waters clear to the surface, and that even if the heavy waters rising were diluted by affluents, they would retain the same general character, whereas the surface waters and the deep waters are chemically entirely different. If there was a tendency for the waters to descend, however, the rocks might naturally draw in fresh water of entirely different character from the outcrop.

Figure illustrating original cavities in a rock of the copper bearing series such as may have been originally filled with chlorine gases, as at "A" wedged in between feldspar belts and an octagonal augite grain.

Van Hise might however suggest that the present distribution of waters is a recent phenomenon, the present circulation being indeed downward, but much later than the origin of the copper.

Now if vapors escape they must be present in proportion to their vapor pressure in the lava and can hardly wholly escape but must be present more or less in the rock moisture of the acid interstices which I have so fully described for the intrusive rocks. But even in an effusive as the rock (above figure) we see that between the crystal of augite and that of feldspar, each having its own shape, is an angular space which must have been originally a pore filled only with gas probably.

In a thoroughly crystalized trap, doleritic melaphyre or diabase the porosity is not over 1 per cent. But in the case of an amygdaloid the amount of vesicular space may have been very considerable, and this space must have been filled either with the original gases or possibly in the case of submarine flows with sea water more or less contaminated with such gases. Such an origin would readily account for the saline character of the waters, and it is worth noting that such saline waters attack copper as is shown by the fixtures around the salt baths of Lower Michigan.

Another most weighty argument is the occurrence of copper native in the iron ores near Crystal Falls.* One can hardly imagine this other than produced by descending waters since the iron ore is universally allowed to have been formed by descending waters. Moreover it occurs in the upper parts of iron ore bodies and is not known to have any connection with lower deposits. It may easily be conceived to have been derived from an over-lying extension of the Keeweenawan, now eroded away.

Pumpelly supposed that the copper may have been originally deposited with the strata, as sulphurets under submarine conditions. He was slightly inclined to call the old lavas altered (metamorphic) sediments.

Irving apparently agreed with Pumpelly speaking of the copper having been arrested in its descent. The more recent writers on ore deposits however seem inclined to refer the origin of the copper deposits to the upward rising waters. For instance Posepny writes as follows:

"Some of the attempted explanations assume, in my opinion correctly, as the cause of the first ore depositions, the action of hot springs—in which connection it is only to be emphasized these thermal effects occurred long after the intrusion of the eruptive flows between the sedimentary strata, so the ores were brought, not by or in the eruptives themselves, but by the later springs, from great depths and perhaps from considerable distances. This explanation, applicable to all deposits, suits also the exceptional case cited by R. D. Irving, namely, the None-

* A. E. SEAMAN writes that he has native copper in iron ores from the Cliffs mine at Iron Mountain, also with ferruginous chert from the tenth level of the Great Western mine, Crystal Falls, also from the Montana mine, Tower, Minn., where it occurs in the iron ore.

such copper bed in the sandstone of Porcupine mountain, far from an eruptive outflow." Posepny seems to have been influenced in the first place by a strong prepossession as to the role of ascending solutions, and in the second place by the occurrence of the ore as a mineral or rarely sulfide and not as carbonate.

Prof. Van Hise in his very interesting article on "Some Principles Controlling the Deposition of Ores," uses the metallic copper deposits as a conspicuous illustration of ore deposits where the concentration by ascending waters has been sufficient without secondary concentration by descending waters, writing as follows:

"In some cases the deposits thus produced are sufficiently rich, so that they are of economic importance. In these cases, which undoubtedly exist, but which perhaps are less numerous than one might at first think, a concentration of ascending waters has been sufficient.

"A conspicuous illustration of ore deposits of this class which may be mentioned are the metallic copper deposits of the lake Superior region. The copper was in all probability reduced and precipitated directly as metallic copper from upward moving cupriferous solutions. The reducing agents were the ferrous compounds in the solid form, in part as magnetite and as solutions derived from the iron bearing silicate. When the copper was precipitated, the iron was changed into the ferric condition. It is well known that metallic copper once formed is but slowly affected by the oxidizing action. Oxidation has, in fact, occurred in the lake Superior region, but from the facts now to be observed, not to an important extent. An oxidized belt may have formed in pre-Glacial times, but if so, it was swept away by glacial erosion, and sufficient time has not yet elapsed to form another. The ore deposits now worked have apparently remained practically unchanged since the time of their concentration. In this fact we have the explanation of the great richness of these deposits to extraordinary depths."

Prof. H. L. Smyth, of Harvard, has also adopted the same belief and I have already discussed it in Vol. VI. of our reports. Prof. Smyth believes that the various flows were surface weathered and the earlier non-alkaline minerals produced thereby. The later alkaline minerals he believes to have been associated with the northerly and northwesternly tilting, and the formation and the filling of the fissures and the impregnation and partial replacement of amygdaloids and conglomerates with copper, the copper not being derived from overlying sandstones nor from traps, but probably by ascending solutions from deep-seated sources.

Returning once more to Prof. Van Hise's paper, we find that however his theories may apply to other deposits, they apply very largely to copper-bearing rocks. His first premise is that the greater number of ore deposits are the result of work of underground water. His second is that the material of ore deposits is derived from rocks within the zone of fracture. This would seem to be true, and shall give some arguments for believing that the copper is derived from the associated igneous rocks. His third premise is that by far the major part of the depositing water is meteoric. By this he means that it is derived from the air, rain water which was worked down into the ground. In view of the composition of the water at considerable depths above given on the Keweenawan range, it seems probable that this is not true, but that the largest part of the water may either have been buried originally with the sediments (possibly he would class this as meteoric), or occluded in the original magna, as he suggests. It is a subject for further investigation, just how much of these three classes of water we have involved.

His fourth premise is that the flowage of the underground water is caused chiefly by gravitative stress. If this is true, and I believe it is, then it follows, as Van Hise himself has remarked (p. 417), that if the copper is most concentrated along the higher parts of the outcrop it must be formed by descending waters; moreover, as he also calls attention (p 412) in case of the minor flexures and pitching folds in the bed, if the waters are descending the richest parts should be in the troughs of these folds, or possibly on lines leading from an anticline down to the trough of the folds. Referring once more to plate 10, of Vol. VI., Part II., it will be seen that in such a case the copper of the Baltic and Trimountain may be expected to chute to the north when followed down. So should the mines around Calumet, while the Quincy mine should chute southwestward. And yet, as the flowage of water is under gravitative stress, it must be remembered that it will take a considerable difference in head for a fresh water to move or balance water with a specific gravity of (1.1898) a fifth more. However, the Keweenawan series consists mainly of a great series of lava flows, many of them over 100 feet thick. (See as an illustration of this, the section of Tamarack shaft No. 5, and correlated beds elsewhere given.) They are not likely to have lost heat for a long time after their effusion, in fact very likely not before their burial under succeeding flows* so that for thousands of years the remnant heat of the effusions and the heat of the later intrusions may have aided the circulation, and particularly the solvent action of the water, as Van Hise (pp. 300, 346, 774), but more particularly J. F. Kemp and others have insisted. And yet the accumulation of copper in the Nonesuch belt of sandy shales, made up of lava and sand, would indicate that it is the chemical character of the lavas rather than their heat which is of most importance. The source of the copper Pumpelly considers to be sulphides originally deposited and bleached out and reduced by the ferrous iron. This may be so, and yet it is strange that we see so little of sulphides in the original rock or of sulphates in the secondary minerals. I have seen some fine selenite from the

* In the succession of flows noted in the Isle Royale drill cores of Vol. VI and the Tamarack shaft, and other sections studied if there had been a long interval between the flows and they had been exposed to air, the amygdaloids would have decayed to red clays and iron ores, and if they had been long enough under water there would have been more or less deposition. As is obvious from the Tamarack section, there is but very little deposition, and while there may have been some contemporary decomposition of the amygdaloids—in fact probably has been, and it may have helped in the copper concentration, yet in very many cases, it is clear that it did not progress far before the next flow came. In fact in some cases an effect on the marginal grain of the underlying flow is indicated. Now, for illustration's sake, if (p. 245 of the Isle Royale report, Fouque and Levy's observations) an ophite cooling in about six days has augite grains 0.03 square millimeters in area, then one which has them about 50 square mm. in area, like the Greenstone 120 feet from the wall, would take about (6x5÷ .03) 10,000 days before it had actually consolidated, that is, it would be between twenty and thirty years before the center of a sheet 240 feet thick had fully consolidated, and it would still be red hot. But the increase of the grain of the augite, clean to the center shows that it must have been during a very early stage of cooling, and at a glance at Plate IV, of the same report shows that after more than ten times that lapse of time say, 200 to 300 years, the temperature at the center would still retain something like an eighth of its original excess of temperature over the country rock. The temperature toward the margin decreases, of course and the total amount of calorics yet left in the flow will be readily found by integrating equation (11) or (12) of the Isle Royale report. Of course the above figures make no pretense to accuracy. We have no right to apply Fouque and Levy's observations on the grain of a rock of one composition off hand to another. Yet the order of figures is likely to be the same, and it is plain that if the Tamarack cross section has some fifty flows, and this section only represents a third or less of the whole pile of flows thus rapidly piled on each other there may have been temperatures near boiling ten thousands of years after the formation of the pile, during all of which time the zeolites we now see may have been forming. Obviously, too, there will be a large amount of energy to promote aqueous circulation.

National mine, but in general sulphates are rare. The arsenides and sulphides that do occur are very peculiar, occurring mainly in the veins, and perhaps rather more frequently as at mount Bohemia, associated with the acid rocks. There are signs that at least at times they are secondary after the native copper. It has occurred to me that possibly a ferrous or ferric chloride containing a trace of copper was an early volcanic emanantion. It is, however, also true that olivine, which is one of the earliest minerals to develop, contains ferrous silicate with which is likely to be associated a trace of copper and nickel. Furthermore, under the microscope the olivine, an early formed mineral, appears to gather at the sides of this dike and the top of the flow. Analyses (Vol. VI. and here) seem to indicate the same thing in the variation of the magnesia and iron.

Thus the copper may have been concentrated. First, with the olivine of the amygdaloid traps; secondly, by leaching out of the olivine which decomposed either by atmospheric action and meteoric waters, or immediately after the outflow of the lava in the presence of the waters, acid and perhaps hot, buried with this formation; thirdly, by reactions due to the circulation downward of this water set up by this uplifting of the edge of the great lake Superior synclinal. It must also be remembered that according to the earlier geologists there has been enormous erosion, which, according to L. L. Hubbard's theory (VI., p. 94), may be in part replaced by a sliding of the upper beds on the lower for miles. In either case there may have been a considerable migration downward, in the porous belts of the formation, of the material of the strata and the original water thereof.

There is yet much to be learned, but three things appear to me to be extremely probable; the copper was associated with the original lava flows; that originally deposited water or gas has been an important factor, possibly merely in bringing copper into solution, and that the water circulation which finally precipitated the copper was downward.

It is apparent, however, that we need to test the rival theories. We need to trace some one horizon some one conglomerate or flow continuously through and survey it carefully and accurately to determine the minor flexures. Dr. L. L. Hubbard has done this in part, but the work is not complete.